2.5-Gb/s BPSK Ultradense WDM Homodyne Coherent Detection Using a Subcarrier-Based Optical Phase-Locked Loop

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Stefano Camatel, *Member, IEEE*, and Valter Ferrero, *Member, IEEE*

***Abstract*—A subcarrier-based optical phase-locked loop is used to build an optical receiver for homodyne coherent detection of wavelength-division-multiplexing 2.5-Gb/s binary phase-shift keying signals. An analysis of the interchannel interference is performed by an evaluation of the effect of channel spacing on the system performance. The presented architecture offers the potential for providing many closely spaced multigigabit channels and enables coherent lightwave technology to become commercially viable.**

***Index Terms*—Homodyne detection, optical phase-locked loops, phase-shift keying (PSK), wavelength-division multiplexing (WDM).**

I. Introduction

THE development of ultradense wavelength-division-multiplexing (UD-WDM) systems is currently under investigation for increasing the global capacity per single fiber. For example in [1], an intensity modulation direct detection (IMDD) 10-Gb/s transmission at 25-GHz channel spacing is demonstrated and studied in detail. It is shown in this and other works that optical filters for UD-WDM have very tight requirements in passband shape and frequency stability. Such requirements can be relaxed adopting coherent detection of received signals.

Coherent optical WDM systems were investigated in the years around 1990 [2]–[4], mainly because they are able to perform WDM demultiplexing in the electrical domain and do not require narrow optical filters. As described in [3], coherent communication systems let transmission of a large number of WDM optical channels with very narrow frequency separations. Another advantage of coherent detection is the ability to select any particular channel by simply tuning a local oscillator (LO). Coherent receivers can be seen as an almost ideal optical filter with very attractive features. Ryu [4] exploited such advantages and experimentally demonstrated coherent detection of 2.5-Gb/s continuous phase frequency-shift keying signals in a WDM optical fiber communication system. In that experiment, heterodyne detection was employed and channels were spaced at 25 GHz. Even if heterodyne detection is easier to implement, it cannot reach channel spacings as narrow as homodyne does [2] and we focused our attention on the last configuration.

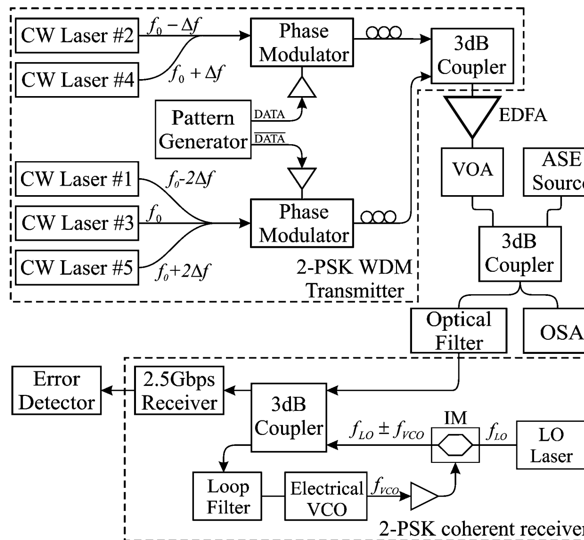

Fig. 1. Experimental setup.

This letter presents experimental results obtained by testing an optical communication system based on homodyne coherent detection of "very ultradense" WDM channels [5]. We analyzed the crosstalk of five channels with adjacent orthogonal polarization; each modulated signal is generated by a 2.5-Gb/s binary phase-shift keying (BPSK) transmitter. Interchannel interference is analyzed by evaluating the effect of channel spacing on the system performance. The employed coherent receiver involves an optical phase-locked loop based on subcarrier modulation (SC-OPLL). The SC-OPLL, described in [6], can be built by using commercial off-the-shelf optoelectronic components.

II. Experimental Setup

The system experimental setup is shown in Fig. 1. Two channel sets were generated by using two PM couplers. The two sets were orthogonal in polarization thanks to the polarization controllers. This way, five continuous-wavelength (CW) lasers at frequencies f_0 (central channel), $f_0 \pm \Delta f$ (orthogonal polarization adjacent channels), and $f_0 \pm 2\Delta f$ (with the same polarization of the central one) were optically multiplexed. Each set of channels were sent to a $LiNbO_3$ 10-Gb/s external phase modulators. Each modulator was driven, respectively, by two electrical nonreturn-to-zero (NRZ) 2.5-Gb/s pseudorandom

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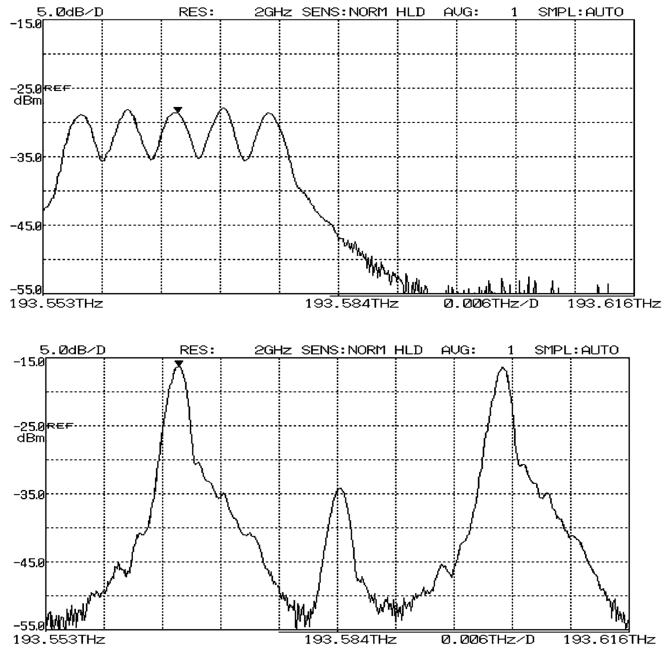

Fig. 2. Spectra of the received UD-WDM signal (top) and of the OVCO output (bottom), 5-GHz channel spacing.

bit sequence (PRBS) signals (DATA and INVERTED DATA) to obtain a BPSK modulation. Transmitted pulse shaping has been performed by using two 2-GHz electrical filters connected at the pattern generator outputs. We used external cavity tunable lasers, whose declared linewidth is lower than 700 kHz, in order to be able to freely set the UD-WDM channel separation Δf. The SC-OPLL, as a pilot carrier coherent optical receiver [7], works properly if each BPSK transmitted signal contains a residual carrier; in practice, this is achieved by incomplete phase modulation at the transmitter side. This operation was performed by applying an NRZ signal of 3.3 Vpp to the phase modulator, which requires 5 V in order to produce a 180° phase shift. Such a configuration generates a BPSK signal with a modulation angle of $\pm 60°$, by leaving a residual carrier containing 25 percent of the transmitted power.

The transmitted signal, whose optical spectrum is shown in the upper part of Fig. 2, is combined with the noise generated by the amplified spontaneous emission (ASE) source. This way the WDM signal total power was kept constant to -5 dBm at the coherent receiver input, and the optical signal-to-noise ratio (OSNR) was changed varying the ASE power level, allowing the system performance evaluation versus the OSNR. The resulting signal is then filtered by a 0.6-nm optical filter, in order to reduce ASE noise, but the optical bandwidth is large enough to let the five channels pass through undistorted, i.e., this filter does not perform any wavelength demultiplexing.

The coherent receiver shown in Fig. 1 is based on our SC-OPLL and includes an optical 3-dB coupler, an amplified photodiode, a loop filter, and an optical voltage controlled oscillator (OVCO). The amplified photodiode has a responsivity of 800 V/W, a bandwidth of 1.8 GHz, and a sensitivity ($\mathrm{BER} = 10^{-9}$) of -22 dBm. The loop filter is a first-order active filter [8] characterized by the time constants $\tau_1 = 59.4$ ns and $\tau_2 = 80.9$ ns. The OVCO is the key element and includes a 20-GHz electrical VCO with 500-MHz/V tuning coefficient, a 32-GHz bandwidth power driver, a 40-GHz $LiNbO_3$ amplitude modulator, and an LO laser. Such an LO laser is an external cavity tunable laser set to work in a CW mode. It is characterized by a declared linewidth lower than 700 kHz and generates a lightwave signal at frequency f_{LO}. The OVCO output power was $+1$ dBm.

The proper operation of OVCO is guaranteed by biasing the Mach–Zehnder amplitude modulator at a null of its transfer function [6]. This way, OVCO produces two main subcarriers at frequencies $f_{\mathrm{LO}} \pm f_{\mathrm{VCO}}$ with a spurious residual carrier at frequency f_{LO}. The LO wavelength has been set in order to allow locking operation between the main subcarrier at frequency $f_{\mathrm{LO}} + f_{\mathrm{VCO}}$ and the transmitted central channel at frequency f_0 (see Fig. 2 top). The measured OVCO output spectrum has been represented in the lower part of Fig. 2. In locking condition, the amplified photodiode shifts the received WDM spectrum to baseband. Indeed, when the SC-OPLL is locked, the photodetector output signal spectrum includes a baseband spectra (centered in zero frequency), generated by the central channel of UD-WDM signal, a spectra centered in Δf and $2\ \Delta f$, respectively, given by the adjacent channels. UD-WDM channel demultiplexing and demodulation is directly obtained through the receiver electrical filter. In fact, the standard receiver filter, such as the synchronous digital hierarchy four-poles Bessel filter at 1.8 GHz, proved more than adequate to reject the two adjacent channels efficiently. In contrast, a standard DWDM receiver, used in IMDD transmission systems, would demultiplex through optical filtering and this is quite impractical at a channel spacing of 5 GHz.

The SC-OPLL closed-loop transfer function introduces a second-order high-pass filtering [8] on the phase of the received signal, whose natural frequency is approximately 8 MHz. Such a high-pass filtering causes a large penalty when the transmitted data present significant spectral components at low frequencies. In order to make the penalty negligible, a $2^7 - 1$ PRBS had to be transmitted. This working condition is not typical in optical transmission systems but does not limit the proof of concept of our PSK UD-WDM transmission system. The problem of pattern dependency can be solved using better linewidth lasers, which allow the PLL to properly work with a lower PLL bandwidth, or upgrading the proposed architecture to a more complex decision driven PLL [9].

Please note that we are using a suboptimum optical receiver, which includes only one photodetector (a balanced receiver is certainly better [8]), but this choice does not affect crosstalk impairments evaluation.

The proposed experimental setup of Fig. 1 is characterized by a phase error standard deviation of almost 5° [6]. The penalty on the system performance due to the phase error is negligible [10]. Furthermore, in our experiment, the ASE noise is the only impairment that influences the performance results presented in Section III, excluding obviously WDM crosstalk.

III. Experimental Results

Performance of our setup was tested by measuring the bit-error rate (BER) as a function of the OSNR (measured over

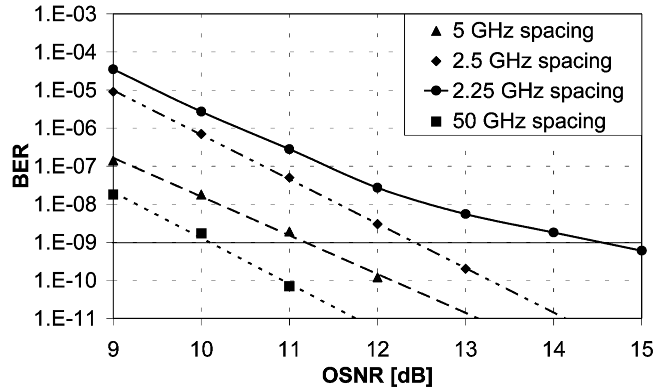

Fig. 3. BER against OSNR (0.1-nm resolution bandwidth) for 50-, 5-, 2.5-, and 2.25-GHz channel spacing values.

0.1-nm optical bandwidth) for several channel spacings. For the reasons reported in the previous section, performance is plotted versus OSNR and not versus the optical power at the receiver because of the negligible electrical noise. The results are shown in Fig. 3 for Δf equal to 50, 5, 2.5, and 2.25 GHz. The curve for $\Delta f = 50$ GHz corresponds to the case without WDM crosstalk; indeed no performance penalty was measured with respect to the case with single-channel transmission. The curve for $\Delta f = 5$ GHz shows approximately 1-dB penalty at BER $= 10^{-9}$, and the penalty is less than 2.5 dB for $\Delta f = 2.5$ GHz. This result proves the feasibility of the proposed setup, even for 2.5-GHz channel spacing. The penalty becomes larger (~4.5 dBm) for $\Delta f = 2.25$ GHz, where the UD-WDM channel spectra significantly overlap, thus giving rise to an intrinsic, receiver independent, channel crosstalk. In our experiment, we demonstrate 1-b/s/Hz spectral efficiency without using multilevel modulation, but only 2.5-Gb/s BPSK with 2.5-GHz channel spacing.

In our experiment, due to hardware limitations, we used only five wavelengths at the transmitter side, which are sufficient as a "proof-of-concept" of our technique. In a practical setup with many UD-WDM channels, when $f_{\mathrm{LO}} - f_{\mathrm{VCO}} = f_0$, the other SC-OPLL subcarrier at $f_{\mathrm{LO}} + f_{\mathrm{VCO}}$ could beat with another WDM channel. This problem can be easily solved by using an optical filter with a passband of the order of $2 \cdot f_{\mathrm{VCO}}$, which could be significantly greater than Δf. In our experiment, we used a 20-GHz electrical VCO, thus envisioning the use of a quite common 40-GHz optical bandwidth (tunable filter, if required by the network architecture).

IV. Conclusion

We have experimentally demonstrated a UD-WDM 2.5-Gb/s BPSK coherent detection with 1-dB penalty at 5-GHz spacing and 2.5-dB penalty with 2.5-GHz spacing, both with orthogonal polarizations. It would be possible to reduce both penalties by "further" pulse shaping optimization at the transmitter side. The use of optical homodyning, greatly mitigates the requirements on optical filtering and enables channel spacing in the few gigahertz range. The price to be paid for optical homodyning is the receiver complexity. Most of the components required in our setup could potentially be integrated using next-generation optical circuits and devices, thus opening new possibilities for future optical transmission systems, and allowing at the same time a reduction in the costs.

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